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THE CONDITIONS OF PREDICTION OF THE PARAMETRIC COMPONENTS OF THE TERMINATION CONTROL SYSTEM OF THE UNMANNED AERIAL VEHICLE FLIGHT PATH

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Abstract. *According to the results of measurements on board of Unmanned Aerial Vehicle the distance vector* $\vec{\mathbf{D}}$ *is formed in the inertial coordinate system, and in mathematical modeling - in the Greenwich system of coordinates. The velocity vector* $\vec{\mathbf{V}}_k$ *is formed by the navigation system in the trajectory coordinate system. Defined by this way the initial conditions gives the possibility to predict the terminal parameters of flight (descent) of Unmanned Aerial Vehicle.*

Keywords: control system of the unmanned aerial vehicle flight path and landing, motion parameters, termination control.

Introduction

A controlled descent (flight) to the specified area of earth surface (circumterrestrial space) of Unmanned Aerial Vehicle (UAV) with a large lift-drag ratio (K>1) is considered. Such vehicles can significantly change their descent (flight) trajectory during an aerodynamic maneuver in the atmosphere and perform landing (hovering) on unexpected distance from the specified point of space.

The task of the control is to guide the vehicle under the action of random disturbances to the point with specified geographical coordinates. Termination control of UAV based on prediction of coordinates of a landing (flight) point is proposed to solve this task [1]. The control of UAV is autonomous because of absence of radio connection on a part of the flight trajectory. Prediction of coordinates is realized by integration of system of differential equations of motion with initial conditions which are determined by autonomous navigation system.

Accumulated navigation error during landing (flight) leads to appearance of dispersion of landing (flight) points [2, 3].

To increase accuracy of UAV guidance after radio contact at the final part of landing (flight) a non-autonomous control is reasonable to use the information about relative position and motion of aircraft and destination point [1]. In this paper the method of synthesis of the non-autonomous termination dual-channel control of UAV $\mathrm{U} = \mathrm{f}(\gamma_a, \mathrm{K})$ by a roll angle $\gamma_a(t)$ and lift-drag ratio $\mathrm{K}(t)$ under guidance to the omnidirectional beacon located in a specified point of space.

The method of non-autonomous multistep adaptive termination control in a zone of close-range guidance, starting at the moment of grabbing of a beacon signal by radio equipment of the vehicle, is used to provide guidance of the vehicle with sufficiently high accuracy [1].

At the moment of grabbing on a board of the UAV an inertial reference frame $Ox_\text{i}y_\text{i}z_\text{i}$ is formed, an origin of the system matches with a centre of gravity of the vehicle, Oy_i axis is directed by radius-vector $\vec{\mathbf{r}}$, and vertical plane $Ox_\text{i}z_i$ is superposed with a radio beacon at a landing point $C(\varphi_\text{c}, \lambda_\text{c})$ with geographic latitude φ_c and longitude λ_c.

A direction vector $\vec{\mathrm{D}}^0(t)$ of a sight line to the beacon and a distance $\mathrm{D}(t)$ to it along the sight line are external information for UAV control system. The internal information is a state vector of the vehicle :

$$\mathbf{x}^\text{н} = (V_\text{к}^\text{н}, \theta^\text{н}, \psi^\text{н}, h^\text{н}, \varphi_\text{ц}^\text{н}, \lambda^\text{н})$$

which is determined in the autonomous navigation system and includes a ground speed $V_\text{к}^\text{н}$, a slope angle of the trajectory $\theta^\text{н}$, a track angle $\varphi^\text{н}$, an altitude $h^\text{н}$, geocentric latitude $\varphi_\text{ц}^\text{н}$ and longitude $\lambda^\text{н}$ [4, 5].

For realization of the data processing in the inertial reference frame for the synthesis of the termination control of the UAV trajectory it is necessary to determine the magnitudes of vectors: the distance from UAV to the responder beacon $\vec{\mathbf{D}}$ and its speed $\vec{\mathbf{V}}_k$ [6, 7, 8].

Formation of conditions for prediction of UAV's motion parameters.

According to the results of measurements on board of UAV the distance vector $\vec{\mathbf{D}}$ is formed in the inertial coordinate system, and in mathematical modeling - in the Greenwich system of coordinates. The velocity vector $\vec{\mathbf{V}}_k$ is formed by the navigation system in the trajectory coordinate system. Defined by this way the initial conditions gives the possibility to predict the terminal parameters of flight (descent) of UAV. Therefore, to determine the vectors $\vec{\mathbf{D}}$ and $\vec{\mathbf{V}}_k$ it is necessary to form in the inertial system the transition matrix from the Greenwich system to the inertial M and the trajectory to inertial Q

$$\left\|\begin{matrix} x_u \\ y_u \\ z_u \end{matrix}\right\| = M \cdot \left\|\begin{matrix} x_{\text{г}} \\ y_{\text{г}} \\ z_{\text{г}} \end{matrix}\right\|, \quad \left\|\begin{matrix} x_u \\ y_u \\ z_u \end{matrix}\right\| = Q \cdot \left\|\begin{matrix} x_\kappa \\ y_\kappa \\ z_\kappa \end{matrix}\right\|. \qquad (1)$$

When a vehicle in motion the inertial coordinate system $Ox_u y_u z_u$ has a constant orientation relative to Greenwich system and the transition matrix between these systems must have constant elements. Taking into account that the system $Ox_u y_u z_u$ is being formed at the moment of the capture of beacon signal, the elements of the matrix M are determined at the same time..

To determine the elements of the matrix M it is necessary to define the reverse transition from $Ox_u y_u z_u$ system to the system $O_{\text{г}} x_{\text{г}} y_{\text{г}} z_{\text{г}}$ with the transposed matrix M^T which elements are determined by three rotations of the $Ox_u y_u z_u$ system at angles $\lambda_u, \varphi_u, \psi_u$.

The first turn is at the angle $\lambda_u = \lambda^н(t_0)$ to the Greenwich system $O_{\text{г}} x_{\text{г}} y_{\text{г}} z_{\text{г}}$ from the auxiliary $O'x'_u y'_u z'_u$ which axis $O' y'_u$ lies in the equatorial plane on the line of its intersection with the meridian plane, which contains a radius- vector of the vehicle mass center, the axis $O' z'_u$ is directed opposite to the angular velocity vector of the Earth's rotation, axis $O' x'_u$ - tangent line to the equator and complements the system to the right (fig. 1):

$$\left\|\begin{matrix} x_{\text{г}} \\ y_{\text{г}} \\ z_{\text{г}} \end{matrix}\right\| = M_1 \left\|\begin{matrix} x'_u \\ y'_u \\ z'_u \end{matrix}\right\| \quad M_1 = \left\|\begin{matrix} -\sin\lambda_u & \cos\lambda_u & 0 \\ \cos\lambda_u & \sin\lambda_u & 0 \\ 0 & 0 & -1 \end{matrix}\right\|.$$

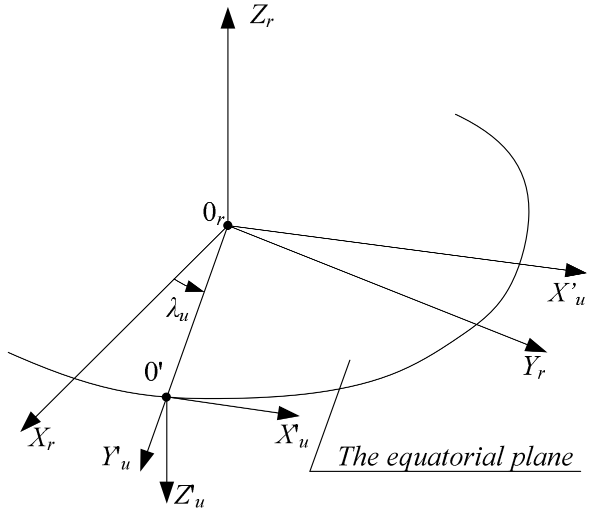

Fig. 1. The first turn of three-turns transition

The second turn occurs at the angle $\varphi_{\text{ц}u} = \varphi^н_u(t_0)$ to the system $O'x'_u y'_u z'_u$ from the auxiliary $O''x''_u y''_u z''_u$, the axis $O'' y''_u$ which is directed along the radius-vector of the vehicle mass center at time t_0 , the axis $O'' x''_u$ is a tangent line to the local parallel, the axis $O'' z''_u$ lies in the local meridian plane and complements the system to the right (fig. 2):

$$\left\|\begin{matrix} x'_u \\ y'_u \\ z'_u \end{matrix}\right\| = M_2 \left\|\begin{matrix} x''_u \\ y''_u \\ z''_u \end{matrix}\right\|, \quad M_2 = \left\|\begin{matrix} 1 & 0 & 0 \\ 0 & \cos\varphi_{\text{ц}u} & \sin\varphi_{\text{ц}u} \\ 0 & -\sin\varphi_{\text{ц}u} & \cos\varphi_{\text{ц}u} \end{matrix}\right\|.$$

The third turn occurs at the relative angle of the path ψ_u from the system $Ox_u y_u z_u$ to $O''x''_u y''_u z''_u$ (fig. 3):

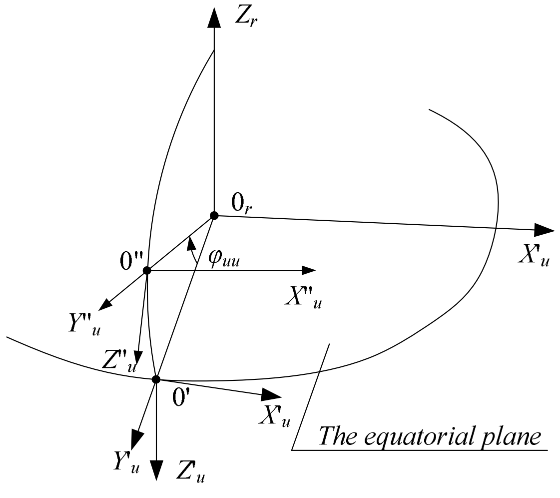

Fig. 2. The second turn of three-turns transition

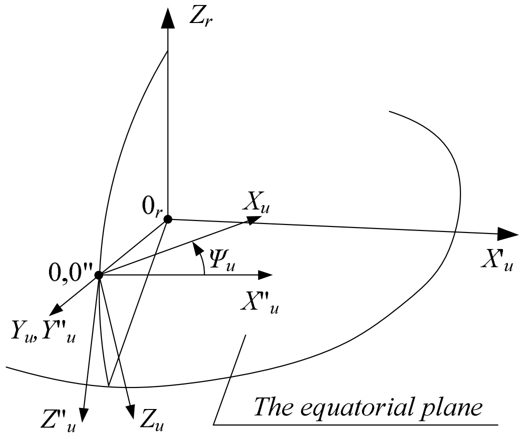

Fig. 3. The therd turn of three-turns transition

The angle ψ_u - is the angle between the two vertical planes, one of which is tangent to plane of local parallel, and the second passes through a given point of landing *C* (fig. 4).

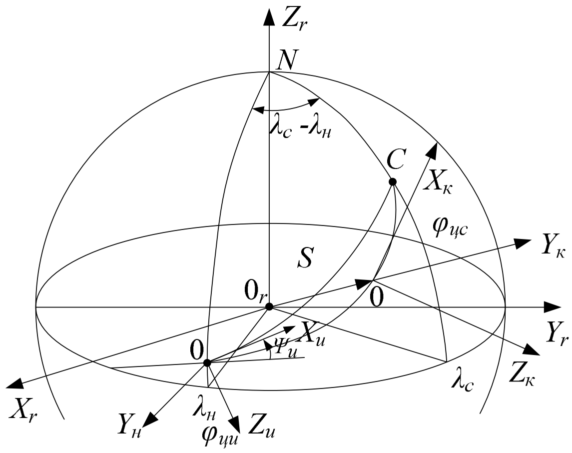

Fig. 4. The completed three-turns transition

For determining the angle of the spherical triangle the arc of a great circle *S* between the points on *O* and *C* is taken

$$\cos S = \sin\varphi_{цu}\sin\varphi_{цс} + \cos\varphi_{цu}\cos\varphi_{цс}\cos(\lambda_{гс} - \lambda_u),$$

then the angle ψ_u

$$\psi_u = \\ = \left\{\frac{\pi}{2} - \arcsin\left[\frac{\cos\varphi_{цс}\sin(\lambda_{гс} - \lambda_u)}{\sin s}\right]\right\}\cdot sign(\varphi_ц - \varphi_{цu}).$$

The coordinate systems $Ox_u y_u z_u$ and $O'' x''_u y''_u z''_u$ is correlated by the following equation:

$$\begin{Vmatrix} x''_u \\ y''_u \\ z''_u \end{Vmatrix} = M_3 \begin{Vmatrix} x_u \\ y_u \\ z_u \end{Vmatrix}, \; M_3 = \begin{Vmatrix} \cos\psi_u & 0 & \sin\psi_u \\ 0 & 1 & 0 \\ -\sin\psi_u & 0 & \cos\psi_u \end{Vmatrix}.$$

As a result, three-turns transition from the system $Ox_u y_u z_u$ to the system $Ox_u y_u z_u$ is done

$$\begin{Vmatrix} x_г \\ y_г \\ z_г \end{Vmatrix} = M^T \begin{Vmatrix} x_u \\ y_u \\ z_u \end{Vmatrix}, \quad M^T = M_1 \cdot M_2 \cdot M_3,$$

that allows to define the matrix M and set the transition (1) from system to another one.

The transition from the trajectory system $Ox_к y_к z_к$ to inertial one $Ox_u y_u z_u$ is carried out by two transitions: the first one - from the system $Ox_к y_к z_к$ to Greenwich system $O_г x_г y_г z_г$, the second one - from Greenwich $O_г x_г y_г z_г$ to inertial system $Ox_u y_u z_u$.

The transition from the system $Ox_к y_к z_к$ to the system $O_г x_г y_г z_г$ is done as a result of four successive rotations of the system $Ox_к y_к z_к$ at the angles $\Theta, \psi, \varphi_ц, \lambda,$ which numerical values are determined by the navigation system at time $t \ge t_0$:

$\Theta(t) = \Theta^н(t)$,

$$\psi(t) = \psi^{н}(t),$$

$$\varphi_{ц}(t) = \varphi_{ц}{}^{н}(t),$$

$$\lambda(t) = \lambda^{н}(t).$$

The first turn is done at the angle Θ from the trajectory system $Ox_{\kappa}y_{\kappa}z_{\kappa}$ to the normal system $OX_{\partial}Y_{\partial}Z_{\partial}$ (fig. 5):

$$\begin{Vmatrix} X_{\partial} \\ Y_{\partial} \\ Z_{\partial} \end{Vmatrix} = \Pi_1 \begin{Vmatrix} x_{\kappa} \\ y_{\kappa} \\ z_{\kappa} \end{Vmatrix}, \quad \Pi_1 = \begin{Vmatrix} \cos\Theta & -\sin\Theta & 0 \\ \sin\Theta & \cos\Theta & 0 \\ 0 & 0 & 1 \end{Vmatrix}.$$

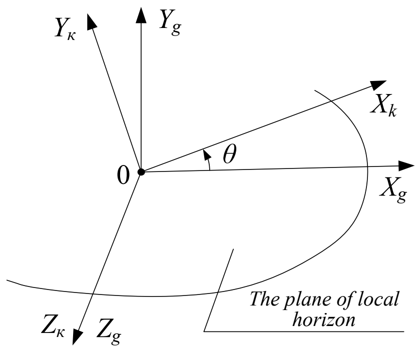

Fig. 5. The first turn of four-turns transition from the system $Ox_{\kappa}y_{\kappa}z_{\kappa}$ to the system $O_{г}x_{г}y_{г}z_{г}$

The second turn occurs at the path angle ψ from the system $OX_{\partial}Y_{\partial}Z_{\partial}$ to the auxiliary system $O'X'_{\partial}Y'_{\partial}Z'_{\partial}$ (fig. 6) which axis $O'X'_{\partial}$ is the tangent line to the local parallel, the axis $O'Y'_{\partial}$ coincides with the radius-vector of vehicle center mass, the axis $O'Z'_{\partial}$ lies in the local meridian plane and complements the system to the right:

$$\begin{Vmatrix} X'_{\partial} \\ Y'_{\partial} \\ Z'_{\partial} \end{Vmatrix} = \Pi_2 \begin{Vmatrix} X_{\partial} \\ Y_{\partial} \\ Z_{\partial} \end{Vmatrix}, \quad \Pi_2 = \begin{Vmatrix} \cos\psi & 0 & \sin\psi \\ 0 & 1 & 0 \\ -\sin\psi & 0 & \cos\psi \end{Vmatrix}.$$

The third turn is done at the angle of geocentric latitude $\varphi_{ц}$ from the system $O'X'_{\partial}Y'_{\partial}Z'_{\partial}$ to the auxiliary system $O''X''_{\partial}Y''_{\partial}Z''_{\partial}$ (fig. 7), with its axis $O''X''_{\partial}$ is parallel to the axis $O'X'_{\partial}$, an axis $O''Y''_{\partial}$ lies at the intersection of the equatorial plane and the local meridian plane, the axis $O''Z''_{\partial}$ lies in the meridian plane and the complements the system to the right:

$$\begin{Vmatrix} X''_{\partial} \\ Y''_{\partial} \\ Z''_{\partial} \end{Vmatrix} = \Pi_3 \cdot \begin{Vmatrix} X'_{\partial} \\ Y'_{\partial} \\ Z'_{\partial} \end{Vmatrix}, \quad \Pi_3 = \begin{Vmatrix} 1 & 0 & 0 \\ 0 & \cos\varphi_{ц} & \sin\varphi_{ц} \\ 0 & -\sin\varphi_{ц} & \cos\varphi_{ц} \end{Vmatrix}.$$

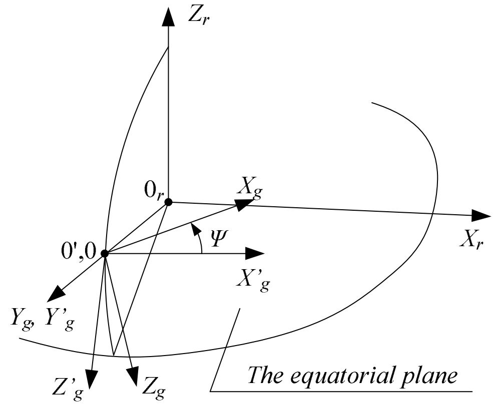

Fig. 6. The second turn of four-turns transition from the system $Ox_{\kappa}y_{\kappa}z_{\kappa}$ to the system $O_{г}x_{г}y_{г}z_{г}$

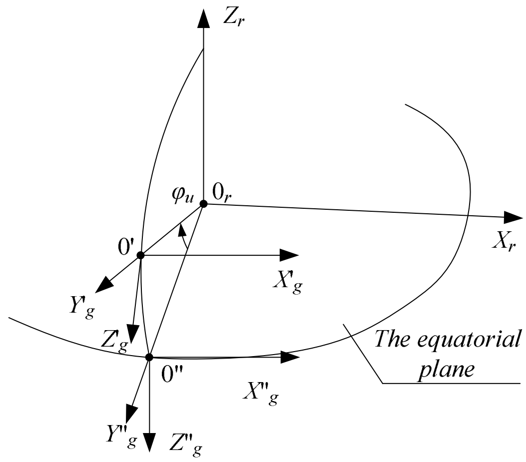

Fig. 7. The third turn of four-turns transition from the system $Ox_{\kappa}y_{\kappa}z_{\kappa}$ to the system $O_{г}x_{г}y_{г}z_{г}$

The fourth turn is done at the angle of longitude λ from the system $O''X''_{\partial}Y''_{\partial}Z''_{\partial}$ to the Greenwich system $O_{г}x_{г}y_{г}z_{г}$ (fig. 8):

$$\begin{Vmatrix} x_{г} \\ y_{г} \\ z_{г} \end{Vmatrix} = \Pi_4 \cdot \begin{Vmatrix} X''_{\partial} \\ Y''_{\partial} \\ Z''_{\partial} \end{Vmatrix}, \quad \Pi_4 = \begin{Vmatrix} -\sin\lambda & \cos\lambda & 0 \\ \cos\lambda & \sin\lambda & 0 \\ 0 & 0 & -1 \end{Vmatrix}.$$

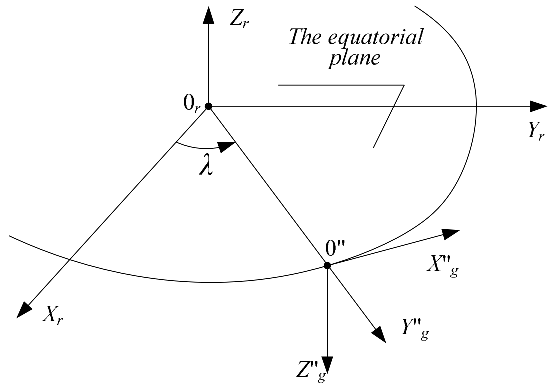

Fig. 8. The fourth turn of four-turns transition from the system $Ox_к y_к z_к$ to the system $O_г x_г y_г z_г$

The four-turns transition from trajectory coordinate system $Ox_к y_к z_к$ to Greenwich one $O_г x_г y_г z_г$ is carried out by using the matrix *П*

$$\begin{Vmatrix} x_г \\ y_г \\ z_г \end{Vmatrix} = П \cdot \begin{Vmatrix} x_к \\ y_к \\ z_к \end{Vmatrix}, \; П = П_4 \cdot П_3 \cdot П_2 \cdot П_1,$$

So, the transition from the trajectory system $Ox_к y_к z_к$ to the inertial one $Ox_u y_u z_u$ is implemented

$$\begin{Vmatrix} x_u \\ y_u \\ z_u \end{Vmatrix} = Q \cdot \begin{Vmatrix} x_к \\ y_к \\ z_к \end{Vmatrix}, \qquad Q = M \cdot П.$$

Velocity vector $\vec{V}_{kj}^{н} = (V_{kj}^{н}, 0, 0)$ is determined by the navigation system in the trajectory coordinate system and is transferred to the inertial one $\vec{V}_{kj} = (V_{kxuj}, V_{kyuj}, V_{kzuj})$

$$\begin{Vmatrix} V_{kxuj} \\ V_{kyuj} \\ V_{kzuj} \end{Vmatrix} = Q \cdot \begin{Vmatrix} V_{kj}^{н} \\ 0 \\ 0 \end{Vmatrix},$$

and the distance vector, defined in the Greenwich system $\vec{D}_j = (D_{xгj}, D_{yгj}, D_{zгj})$, also translated to the inertial one $\vec{D}_j = (D_{xuj}, D_{yuj}, D_{zuj})$

$$\begin{Vmatrix} D_{xuj} \\ D_{yuj} \\ D_{zuj} \end{Vmatrix} = M \cdot \begin{Vmatrix} D_{xгj} \\ D_{yгj} \\ D_{zгj} \end{Vmatrix}.$$

Angle α_j is formed by the line of sight $\vec{D}_j$ and the plane of local horizon, taking place through the point of landing *C* (fig. 9),

$$\alpha_j = \arcsin\left(\frac{H_j}{D_j}\right), \; H_j = r_j - (\vec{r}_c \cdot \vec{r}_j).$$

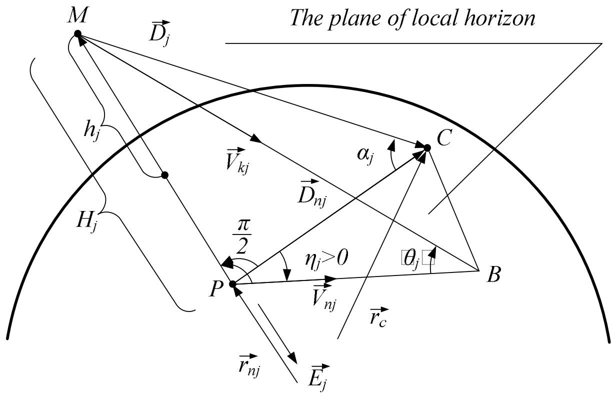

Fig. 9. The determination of angle conditions

Relative angle of course η_j represents the angle between the projections $\vec{D}_{nj}$ and $\vec{V}_{nj}$ vectors $\vec{D}_j$ and $\vec{V}_{kj}$ on the local horizon plane (fig. 9). To determine these projections the radius-vector $\vec{r}_{nj}$ of intersection point of horizon plane with the radius-vector of vehicle mass center is defined

$$\vec{r}_{nj} = (r_{nxгj}, r_{nyгj}, r_{nzгj}),$$

$$r_{nyгj} = (r_j - H_j)\cos\varphi_{цj} \sin\lambda_j,$$

$$r_{nxгj} = (r_j - H_j)\cos\varphi_{цj} \cos\lambda_j,$$

$$r_{nzгj} = (r_j - H_j)\sin\varphi_{цj}.$$

Vector $\vec{D}_{nj}$ is determined by the vector equation $\vec{D}_{nj} = \vec{r}_c - \vec{r}_{nj}$, which is expressed through the projections in the Greenwich system of coordinates

$$\vec{D}_{nj} = (D_{nxгj}, D_{nyгj}, D_{nzгj})$$

$$D_{nxгj} = r_{cxг} - r_{nxгj}, \quad D_{nyгj} = r_{cyг} - r_{nyгj},$$

$$D_{nzгj} = r_{czг} - r_{nzгj}.$$

Then vector $\vec{D}_{nj}$ from Greenwich coordinate system is transformed to the inertial one $\vec{D}_{nj} = (D_{nxuj}, D_{nyuj}, D_{nzuj})$

$$\begin{Vmatrix} D_{nxuj} \\ D_{nyuj} \\ D_{nzuj} \end{Vmatrix} = M \cdot \begin{Vmatrix} D_{nxгj} \\ D_{nyгj} \\ D_{nzгj} \end{Vmatrix}.$$

Velocity vector $\vec{V}^{н}_{kj}$ is specified in the trajectory coordinate system $\vec{V}^{н}_{kj} = (V^{н}_{kj}, 0, 0)$ and its projections on the local horizon plane $\vec{V}_{nj}$ are components of the vector $\vec{V}_{kj} = (V_{kx\partial j}, V_{ky\partial j}, V_{kz\partial j})$

$$\begin{Vmatrix} V_{kx\partial j} \\ V_{ky\partial j} \\ V_{kz\partial j} \end{Vmatrix} = \Pi_1 \cdot \begin{Vmatrix} V^{н}_{kj} \\ 0 \\ 0 \end{Vmatrix}, \quad \begin{aligned} V_{kx\partial j} &= V^{н}_{kj} \cos\Theta_j, \\ V_{ky\partial j} &= V^{н}_{kj} \sin\Theta_j, \\ V_{kz\partial j} &= 0, \end{aligned}$$

on an axis OX_∂ of normal (moving) coordinate system

$$\vec{V}_{nj} = (V^{н}_{kj} \cos\Theta_j, 0, 0) \qquad (2)$$

Vector $\vec{V}_{nj}$ (2) is newly transferred to the trajectory coordinate system $\vec{V}_{nj} = (V_{nxкj}, V_{nyкj}, V_{nzкj})$

$$\begin{Vmatrix} V_{nxкj} \\ V_{nyкj} \\ V_{nzкj} \end{Vmatrix} = \Pi_1^T \cdot \begin{Vmatrix} V^{н}_{kj} \cos\Theta_j \\ 0 \\ 0 \end{Vmatrix}, \quad \begin{aligned} V_{nxкj} &= V^{н}_{kj} \cos\Theta_j \cos\Theta_j, \\ V_{nyкj} &= V^{н}_{kj} \cos\Theta_j \sin\Theta_j, \\ V_{nzкj} &= 0, \end{aligned}$$

then determined in the inertial system $\vec{V}_{nj} = (V_{nxuj}, V_{nyuj}, V_{nzuj})$

$$\begin{Vmatrix} V_{nxuj} \\ V_{nyuj} \\ V_{nzuj} \end{Vmatrix} = Q \cdot \begin{Vmatrix} V_{nxкj} \\ V_{nyкj} \\ V_{nzкj} \end{Vmatrix}.$$

Two vectors $\vec{D}_{nj}$ and $\vec{V}_{nj}$ determine: the vector product $\vec{E}_j = (E_{xuj}, E_{yuj}, E_{zuj}) = \vec{D}_{nj} \times \vec{V}_{nj}$ and the main vector value of the course angle by means of values of its two functions -

$$\sin\eta_{oj} = \frac{\left|\vec{E}_j\right|}{\left|\vec{D}_{nj}\right| \cdot \left|\vec{V}_{nj}\right|};$$

$$\cos\eta_{oj} = \frac{\left(\vec{D}_{nj} \cdot \vec{V}_{nj}\right)}{\left|\vec{D}_{nj}\right| \cdot \left|\vec{V}_{nj}\right|}.$$

For orientation of the velocity vector $\vec{V}^{н}_{kj}$ relatively to the point of landing C [4-6], a rule of signs is introduced for the course angle: the angle is positive, if the point of landing is located on the left of the vertical plane passing through the velocity vector $\vec{V}^{н}_{kj}$:

$$\eta_j = \begin{cases} \eta_{oj}, & \eta_{oj} \le \pi, \\ \eta_{oj} - 2\pi, & \eta_{oj} > \pi. \end{cases}$$

Conclusions

Using the results of measurements on board of UAV the distance vector $\vec{\mathbf{D}}$ is formed in the inertial coordinate system, and in mathematical modeling - in the Greenwich system of coordinates. The velocity vector $\vec{\mathbf{V}}_k$ is formed by the navigation system in the trajectory coordinate system. Obtained in this way the initial conditions give the possibility to predict for each correction point of control of finite-difference model of motion the terminal parameters of flight (descent) of UAV.

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